The Physics of Sound Scattering From, and Attenuation Through, Compliant Bubbly Mixtures

Ronald A. Roy
Dept. of Aerospace and Mechanical Engineering, Boston University
110 Cummington Street, Boston, MA 02215
phone: (617) 353-4846   fax: (775) 201-4417email: ronroy@bu.edu

William M. Carey
Dept. of Aerospace and Mechanical Engineering, Boston University
110 Cummington Street, Boston, MA 02215
phone: (617) 353- 7706   fax: (617) 353-5866   email: wcarey@bu.edu

LONG-TERM GOALS

The goal of this research is to acquire a quantitative understanding, leading to predictive models, of the broader aspects of linear and nonlinear sound scattering, transmission and coherency in oceanic bubbly mixtures pertinent to the shallow-water acoustics. This includes a conceptual understanding of the role played by damping and stabilization mechanisms in bubble dynamics and longevity. Of particular interest is the delineation of different regimes of behavior as a function of frequency, size distribution, flow and volume fraction.

OBJECTIVES

An objective specific to this project is the extension of the theory of sound transmission and coherency in bubbly liquids to derive attenuation characteristics for both small amplitude (linear response) and large amplitude (nonlinear response) forcing, ultimately incorporating the effects of contaminating surface-active solutes. A second objective is the development of a unique laboratory capability for the precise and accurate measurement of the frequency-dependent complex acoustic impedance of, scattering from, and the coherency of propagation through well-characterized bubble ensembles *for frequencies spanning the individual bubble resonance frequencies*. Characterization implies the precise knowledge of the space- and time-dependent bubble density and size distribution.

APPROACH

The approach involves a balance between theory, analytical modeling and experiments to predict and measure propagation, scattering, and coherency characteristics. The dynamics of a single bubble for both small and large amplitude forcing and is treated numerically using the Keller formulation for bubble dynamics in a Newtonian viscous fluid. Attributes of bubble behavior (mainly damping and resonance response) can be quantified and incorporated into a comprehensive description of sound propagation, scattering and coherency by extending the Wood-Foldy-Morse theories. The final step is to incorporate the effect of surface active materials by adapting numerical models developed by Church [1] and Allen & Roy [2,3], among others.

Report Documentation Page

1. REPORT DATE **30 SEP 2001**	2. REPORT TYPE	3. DATES COVERED

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
The Physics of Sound Scattering From, and Attenuation Through, Compliant Bubbly Mixtures	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Dept. of Aerospace and Mechanical Engineering,,Boston University,110 Cummington Street,,Boston,,MA, 02215**	8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT
The goal of this research is to acquire a quantitative understanding, leading to predictive models, of the broader aspects of linear and nonlinear sound scattering, transmission and coherency in oceanic bubbly mixtures pertinent to the shallow-water acoustics. This includes a conceptual understanding of the role played by damping and stabilization mechanisms in bubble dynamics and longevity. Of particular interest is the delineation of different regimes of behavior as a function of frequency, size distribution, flow and volume fraction.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**7**	

Laboratory experiments cover two fronts of activity. FY01 efforts focused on the measurement of the complex surface impedance of bubble distributions terminating a sound-hard impedance tube over frequencies ranging from well below to well above bubble resonance. From this, the frequency dependent sound speed and attenuation is inferred. The bubbly medium can also be characterized optically using a stereo microscope and acoustically using a standing wave apparatus to determine void fraction in the Woods limit. From this, the frequency-dependent phase velocity and attenuation of the bubbly medium is computed using a model. The direct comparison of measured and computed dispersion curves permits us to verify the measurement scheme and/or refine the model. We believe this approach will be particularly powerful when applied to hard-to-model situations such as very dirty bubbles, bubbles in viscoelastic media, and even bubbles trapped in sediments.

The second experimental thrust for FY01 is the use of optical Mie scattering to measure the dynamic response of single bubbles suspended in a viscoelastic holding medium (Xanthan gum). This material has been used extensively for experiments in which bubbles distributions are "frozen" in space for purposes of facilitating detailed study [4]. The laser-based Mie scattering approach for monitoring bubble motion [5] provides a non-invasive measure of the instantaneous bubble radius as a function of time. This yields the frequency dependent response for acoustically driven bubbles for comparison with Newtonian viscous theory and (eventually) bubble dynamics models based on non-Newtonian fluid rheology. This measurement technique, when used in conjunction with a low-Q acoustic resonator, admits the study of frequency-dependent bubble response as a function of acoustic forcing and bubble size – all for frequencies spanning the bubble resonance and all in the absence of any boundaries.

Modeling continues to be focused on the development of a comprehensive and self contained formalism for describing the acoustics properties of bubbly liquids, drawing from the classical efforts of Wood, Foldy, Morse and others. This has been supplemented by a parallel effort aimed at developing 1st-order correction terms that account for the surface elasticity and dilatational viscosity of surface-active layers similar to those that can coat oceanic bubbles.

WORK COMPLETED

In FY01, laboratory experiments were conducted to explore the acoustic impedance of well-characterized assemblages of bubbly fluid. The notion is that by measuring the surface impedance of bubbly assemblages, one can determine their dispersive properties (both sound speed and attenuation) for void fractions too great to support conventional standing wave and through transmissions methods.

Completion of Impedance Tube Facility and System Verification

The cross calibration problems have been solved using a technique [6] which involves the use of three known terminations. These are a water-filled tube with pressure release termination for three different tube lengths. Each length was chosen such that both resonance and anti-resonance of the termination was avoided. This technique eliminated the uncertainty associated with estimation of losses. These results were verified using a different length than those of the calibration. This type of termination offers a well known complex and frequency-dependent standard for ground truth system calibration. A typical result is shown in Fig. 1.

Since the goal is the development of a sea-going instrument, a separate technique was developed which requires no *in situ* calibration, and at the same time increases the frequency range. This new technique [7] is a variation of the standard transfer function technique, but utilizes a single sensor instead of two, hence cross-calibration is not required. The single sensor is used first at one position and then the other. For each position, the transfer function between the hydrophone signal and the source signal is measured. As long as the source signal and the sample remain constant, the desired transfer function between the two hydrophone signals can be calculated. This implementation yields ground truth results identical to the two-sensor method shown in Fig. 1, while extending the frequency range of the existing tube down to 2 kHz.
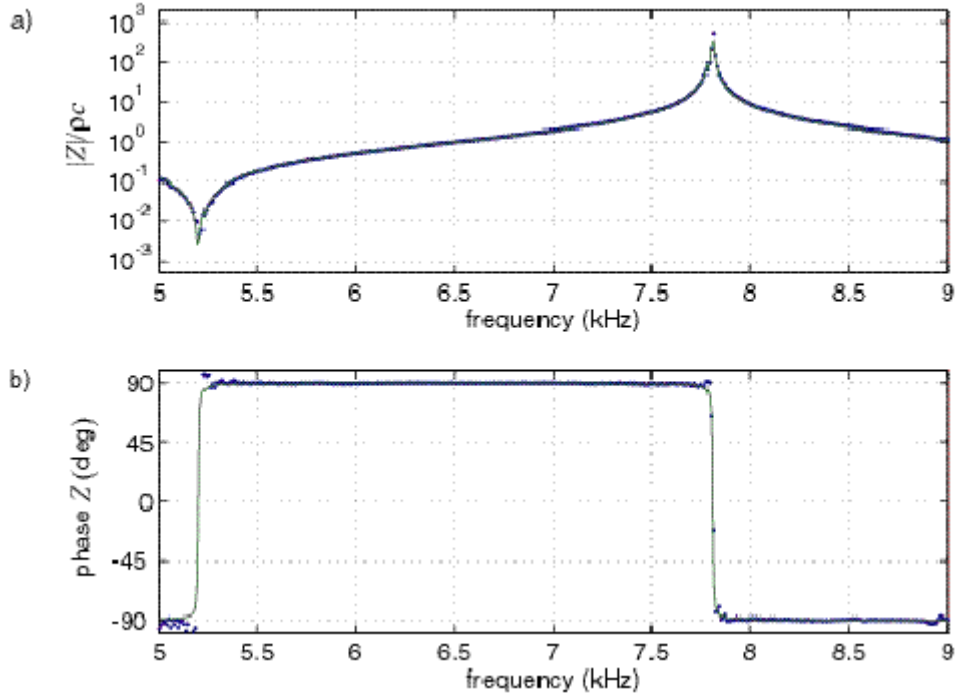

Figure 1. The measured (dots) and predicted (solid lines) impedance of a pressure-release-terminated, water-filled transmission line is shown as a system verification for the two-sensor, three-calibration technique. The magnitude, normalized by the specific acoustic impedance of water, is shown in a) and the phase is shown in b).

Mie Scattering Apparatus for the Study of Driven Bubble Dynamics

An apparatus was developed for studying the dynamics of single bubbles in the absence of nearby boundaries. It features a "nearly rectangular" (i.e. no parallel sides) acoustic resonator filled with xanthan gum, is instrumented to operate between 5 and 50 kHz. and the sound field is monitored with a needle hydrophone. A single bubble is suspended in a gel and is then driven acoustically with a sinusoidal signal or a sinusoidal signal with a slowly varying frequency. The instantaneous bubble response is determined by measurement of the He-Ne laser light (Mie) scattering with a large aperture detector positioned at the critical angle. The proper selection of this angle and aperture size permits

the relation of the scattered photon flux to the surface area of the bubble. Consequently the instantaneous bubble radius can be determined with a precision limited only by the signal-noise ratio and the signal bandwidth. In addition a Leica stereo microscope is used to independently measure the size of the bubble because the bubble response is size dependent and this information is used to calibrate the optical detector.

This apparatus has been assembled ,manually tested and the data acquisition algorithms and signal processing algorithms that correct for the frequency dependent pressure field in the cell are being refined. The initial experiments are focusing on the measurement of the frequency and size dependent response of a bubble for comparison with predictions from a Newtonian fluid model.
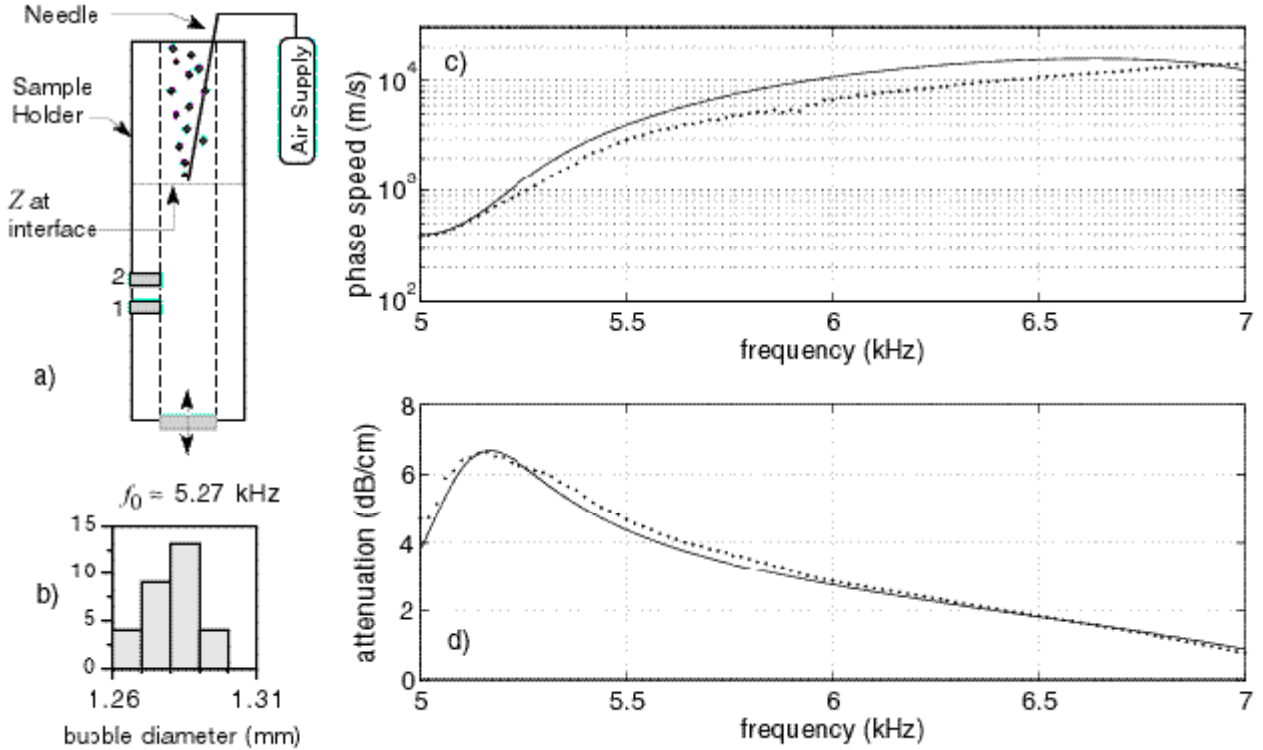

Figure 2. The schematic diagram in a) depicts the two-sensor measurement system and the bubble injection scheme. A histogram of the bubble sizes is shown in b), and the void fraction was 0.64%. The measured (dots) and predicted (solid lines) phase speed and attenuation for propagation in these bubbles is shown in c) and d), respectively. The predicted values are obtained from [REF].

RESULTS

Measurement of Bubbly Liquid Propagation Characteristics Across Resonance

The impedance tube system was used with the two-sensor, three-calibration technique to measure propagation characteristics for air bubbles in water. The bubbles were injected into the sample holder using a single needle. The void fraction was 6.4×10^{-5}, determined by use of a low frequency

resonator technique. The bubble size distribution was measured photographically and used as an input into Commander and Prosperetti's model [8] for comparisons shown in Fig. 2. This formulation was found to describe the sonic speed in the region of the resonance frequencies of the bubbles (5.2 kHz) quite well; however deviations were observed at higher frequencies. In order to obtain the propagation characteristics from the impedance measurement, no energy entering the sample holder can return into the impedance tube after reflection off the open end. Attenuation by the bubbles assures this near resonance, but could prevent accurate measurements at higher frequencies. The bubble injection apparatus has been expanded from one to twelve needles and produced 1% VF samples with a narrower bubble size distributions to resolve this problem.

The results shown in Fig. 2 are unique and show a time-resolved snapshot of the frequency-dependent attenuation and sound speed for a bubbly distribution. In the past, measurement of this nature would take hours of tedious effort and would ultimately be compromised by insidious changes in the bubble size distribution or number density. These results were obtained in seconds. Also there are very few examples in the literature of measurements of near-resonance c and α for high VF flows because sound transmission through the medium is attenuated. The resonator techniques can be used at lower void fractions, however the extremely large attenuations associated with high VFs make standing wave techniques difficult or impossible. This technique can measure dispersion below, at and above resonance for high-VF flows and do it repeatedly with 1-s temporal resolution.

IMPACT/APPLICATIONS

That bubble clouds can be driven to pulsate collectively is important to any assessment of scattering and attenuation from oceanic bubble clouds and layers. This research is important to the understanding of high frequency shallow water noise, propagation, mine hunting sonar systems, high power acoustic MCM arrays, and wake homing torpedoes. Furthermore, the acoustical measurement of bubble populations and circulation patterns depends on the physics of multiple scattering and absorption in bubbly mixtures. The persistence of micro-bubbles in the shallow water column are the limiting factor determining the resolution of sonar systems and needs to be quantified. Finally, this impedance tube technology being used to study bubbly liquids is well suited to the measurement of dispersion in sediments (both fully and partially saturated).

RELATED PROJECTS

1. A collaboration with K. Commander of CSS and K. Williams of APL/UW involving the use of the impedance tube to measure sediment acoustics below 10 kHz has been proposed.

2. A collaboration with the NRL has been proposed. Meetings have been held with Dr. Franchii and his staff at NRL.

REFERENCES

1. C.C. Church. 1995, J. Acoust. Soc. Am. **97**, 1510-21.

2. J.S. Allen and R.A. Roy, "Dynamics of gas bubbles in viscoelastic fluids I. Linear viscoelasticity," J. Acoust. Soc. Am. **107**(6), 3167-3178.

3. J.S. Allen and R.A. Roy, 2000b, "Dynamics of gas bubbles in nonlinear viscoelastic media," J. Acoust. Soc. Am. **108**, 1640 (2000).

4. P.A. Hwang, R.A. Roy and L.A. Crum, "Artificial bubble cloud targets for underwater acoustic remote sensing, J. Atmos. and Ocean Tech. **12**, 1289-1302 (1995).

5. R. G. Holt and L. A. Crum, "Mie scattering used to determine spherical bubble oscillations," Applied Optics **29**, 4182-4191 (1990).

6. V. Gibiat and F. Laloë, "Acoustical impedance measurements by the two-microphone-three-calibration (TMTC) method," J. Acoust. Soc. Am. **88**, 2533–2545 (1990).

7. W. T. Chu, "Transfer function technique for impedance and absorption measurements in an impedance tube using a single microphone," J. Acoust. Soc. Am. **80**, 555-560 (1986).

8. K. W. Commander and A. Prosperetti, "Linear pressure waves in bubbly liquids: Comparison between theory and experiments," J. Acoust. Soc. Am. **85**, 732–746 (1989).

PUBLICATIONS

P.W. Wilson, R.A. Roy, and W.M. Carey, "The effect of cloud shape on acoustic scattering from laboratory bubble clouds," Acoust. Res. Lett. Online **2**(4), 103-108 (2001).

Roy, R.A., Wilson, P.S. and Carey, W.M., "Some new experimental insights into the acoustics of bubbly liquids," in Proceedings of the 17th International Congress on Acoustics, September 2001. In press.

Carey, W.M. and Roy, R.A., "Radiation and scattering from micro-bubble clouds," in Proceedings of the 17th International Congress on Acoustics, September 2001. In press.

J.S. Allen and R.A. Roy, "Dynamics of gas bubbles in viscoelastic fluids I. Linear viscoelasticity," J. Acoust. Soc. Am. **107**(6), 3167-3178.

W. Carey, " Oceanic Low Frequency Ambient Noise" in Proceedings Of the MTS/IEEE Oceans 2000, Providence RI, 2000.

W.M. Carey and R.A. Roy, "The low frequency radiation and scattering of sound from bubble clouds," in Proceedings of Oceans 2000 Vol. 2, 1077-1084, 2000.

W. Carey, " Array Measurements and Characterizations with Relative Velocity as a Parameter" in Proceedings Of the MTS/IEEE Oceans 2000, Providence RI, 2000.